A MATERIALS APPROACH IN THE DEVELOPMENT OF MULTI-THREAT WARFIGHTER HEAD PROTECTION

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ABSTRACT

The United States has historically capitalized on material and process advances to develop improved ballistic head protection for the warfighter. This also includes innovations in the design of various helmet elements based on careful consideration of the environment, patterns of use, interfacing with other equipment (e.g., weapons, body armor), and possible threat scenarios. As such the U.S. helmet has evolved in both shape, composition, and manufacture, and this same trend – driven largely by contemporary and anticipated demands – has provided an excellent opportunity to consider new levels of protection and complexity. Increased ballistic mass efficiency has traditionally been the most significant factor, but advances in materials and computational tools have made possible new approaches to address helmet pad and suspension systems, as well as higher levels of ballistic resistance through hybridization. Helmet shell material and design, padding, and suspension have significant influence over several areas including shock resistance (due to a non-penetrating fragment or bullet, or to a blast event), as well as comfort and thermal management. This paper provides an overview of novel material, processing, and concept development to provide a set of both modular and integrated tools and technologies for tailoring helmet performance.

1. INTRODUCTION

The past decade has seen the maturation of several technologies that provide an unprecedented opportunity to revisit traditional design and manufacture of Army materials, systems, components, and equipment. While these systems may be diverse, ranging from portable shelters, to backpack unmanned aerial vehicles (UAV's), to enhanced ground and rotorcraft platforms, they often share common logistical and operational constraints. Among the most dominant and pervasive of these is overall system weight. Excessive weight can hinder rapidity of deployment (Figure 1), excessively consume critical resources in theatre (e.g., fuel, water), and often burden the warfighter's mobility to a level that could (under certain circumstances) impede his or her performance as well as survivability. Thus, innovations in materials technology have been especially critical in retaining the needed level of protection at a weight that enables execution of the given mission. New materials bring with them new challenges, both in design and manufacture. The goal in developing new materials is to provide the warfighter with a decisive advantage. Prudent selection of these materials, based on performance requirements and weight and volume constraints, ultimately limit the range of candidate materials for new systems applications.

Fig. 1 Warfighter with Equipment

2. BACKGROUND

Personnel protection encompasses a range of solider-borne equipment and technologies. The scope of this work is limited to the helmet only. However, it should be noted that given the modern warfighter ensemble, consideration must be given at some level to the helmet as part of a larger system of protection [McManus, 1976; Riewald, 1991; Dean, 1920]. For example, the U.S. Army systematically replaced the PASGT (Personnel Armor System Ground Troop) with the Advanced Combat Helmet (ACH) based on requirements for enhanced interfacing with other soldier equipment. The forward "brim" of the PASGT made sighting some weapons difficult, and the rear edge of the PASGT could, in certain positions, impinge on the body armor worn on the back.

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Traditionally, protection of the head has implied the use of a ballistic material that reduces the chances of perforation, reduces the energy of the residual fragment and limits the trauma associated with fragments [Yang, 1993; Scott, 2006; Cunniff, 1999]. A more generalized description of protection is shown in Figure 2, wherein a "survivability envelope" has been constructed for the helmet and the head. It presumes that the ultimate goal is to prevent any catastrophic damage to the brain. The use of camouflage indicates a means of reducing warfighter vulnerability to detection. Thereafter, the helmet, padding, and to a degree the skull provide the remaining resistance to fragmentary threats. Figure 2 illustrates the highly coupled nature of both protection helmet materials and human skull and brain; this has critical implications for both ballistic and blast induced events.

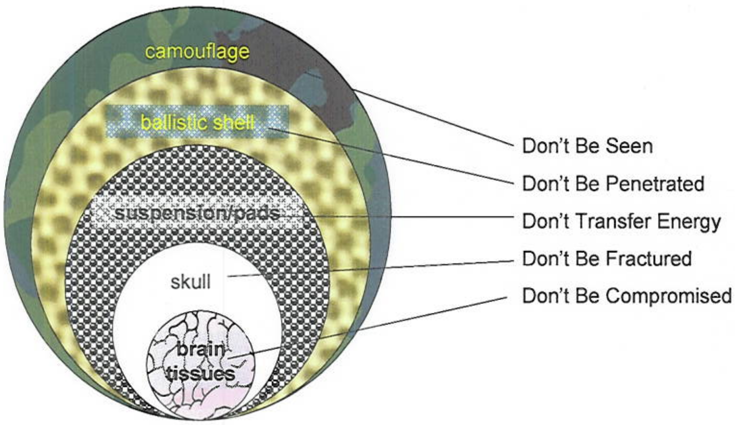

Fig. 2 The Survivability Envelope for Head

3. APPROACH

The ACH helmet – and more specifically, the ballistic performance of the ACH helmet – serves as an effective baseline for evaluating not only new materials, but more generally, it provides a benchmark to compare overall "system" response. The incumbent ballistic material in the ACH is a rubber (PVB) modified-phenolic matrix reinforced with woven aramid fibers. Commercial sources of aramids include Kevlar™ and Twaron™. The ballistic performance of these materials when molded into both flat plate and helmets is often different [Cunniff, 1999; Walsh, 2008], therefore it is typically recommended that both tests be conducted and compared to determine how well the ballistic performance is preserved in the "as formed" shell.

The implications of materials with improved ballistic mass efficiency are four-fold. First, it is possible to consider producing a helmet that weighs less than the ACH, but provides the same level of ballistic protection. It should be noted that as weight is reduced via the use of alternative materials (typically of lower modulus), consideration must be given to other properties besides ballistic performance. For example, the structural rigidity of the helmets may be less due to both a lower cross-section moment of inertia (thinner shell) and more compliant materials in the shell.

The second implication of improved ballistic mass efficiency is the opportunity to deliver a *higher* level of ballistic performance at the *same* total weight as the incumbent helmet with the same protected surface area. The third is to increase the total area of head coverage at the same weight of the current ACH shell keeping the protection level constant. Finally, the fourth opportunity is address higher level threats of varying degree (e.g., more severe projectiles). The options are shown against the baseline in Figure 3.

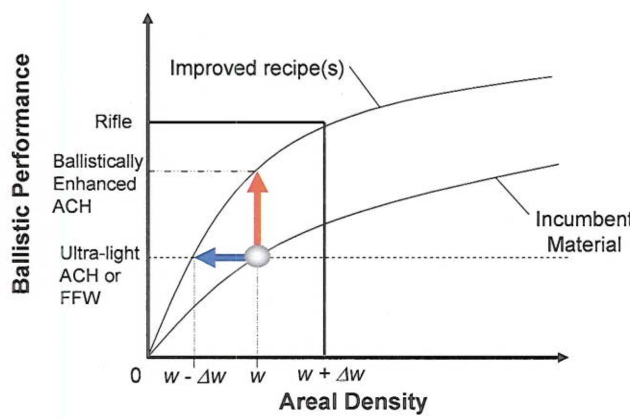

Figure 3. Implications of Improved Ballistic Mass Efficiency

3a. CANDIDATE MATERIALS

Research in the development of new materials for helmet systems can be divided into two basic areas. The first is the development of wholly new materials from advances in chemistry, polymer science, metallurgical science, and related sources of innovation. The second is the use of commercially available materials in new combinations, architectures, and geometries [Walsh, 2007]. Combined, both of these provide near term and longer term technologies that will sustain and improve overall warfighter protection. The implications of commercial availability can not be underestimated; it has the potential to either limit or exclude the use of superior materials if the number of systems required far exceeds domestic capacity. Hence, the importance of innovations in processing technology as well; the newer material

combination may require different manufacturing procedures, tooling and likely capital investment.

The selection of new candidate materials generally begins with a consideration of the specific properties. Figure 4 is a traditional "map" of modulus vs. density, and provides a basic illustration of these material properties. While Figure 4 is an effective starting point, it fails to provide detail on combinations of materials in various forms (films, fibers, layers) or more typically, fiber reinforced composite laminate properties. The implications of this are significant. For example, previous work was demonstrated that combining dissimilar materials [Walsh, 2007; Bless, 1999; Woodward, 1994]] can provide superior ballistic or structural response; the constituent materials may be superior in one or the other aspects, but the hybridized solution enables the desired and complete set of properties.

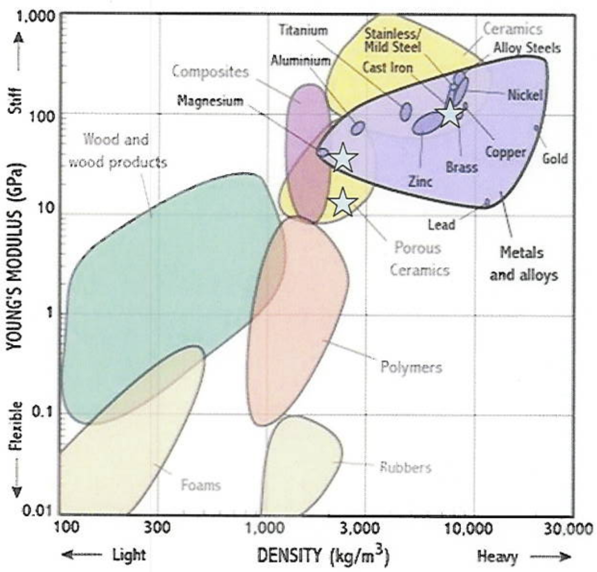

Figure 4. Material Palette

AN INTEGRATED APPROACH TO NEW MATERIAL DEVELOPMENT

The introduction of polymer composites in the 1970's into the ballistic helmet shells represented a materials revolution: organic, man-made fibers and resins were replacing traditional metallic materials. Note that the WWII M1 steel helmet actually included a composite inner liner with similar phenolic resin from which the current ACH molding process originated. Since then, innovations primarily in the aramid fibers and fabric architecture have been largely responsible for the ballistic performance gains in the MICH and ACH helmets. While not new, other combinations of fibers, architectures and organic matrices with superior ballistic performance have emerged over time. These principally include, but are not limited to, thermoplastic matrix / woven aramids (e.g., DuPont's Mark III system), Dyneema and Spectra fibers in thermoplastic matrices with cross plied unidirectional architectures. Previous research efforts have demonstrated, in limited testing, the potential advantages of thermoplastic (matrix and/or fiber)-based systems.

Carbon, glass, and a variety of organic based fibers were considered as a light weight means of providing structural stiffness to the relatively compliant laminates of thermoplastic fibers and/or matrices. Expansion of this hybridization work eventually lead to re-examining the role of metals in helmets systems. As stated earlier, metals (namely steel) had been the armor material of choice prior to the invention of the high tenacity fibers. Since then, steel has all but disappeared from helmets. While some have explored the use of aluminum and titanium shells, the overall performance gains were not significant enough to warrant the subsequent processing, interfacing and durability concerns.

One metal which has demonstrated some promise in both structural and ballistic applications is magnesium alloy, of varying composition. Magnesium is relatively light, with a specific gravity (1.74) comparable to Kevlar fiber (Fig. 5). However, pure magnesium is not effective ballstically as its alloy variants: the average S.G. for magnesium alloys such as AZ31B-0 is 1.78g/cc. Nevertheless, as shown in Figure 5, its density is within the range of the "traditional" palette of materials considered for personnel protection. In addition to its relatively light weight, magnesium has good specific stiffness and damping properties, both of which could prove beneficial in resisting ballistic and blast events.

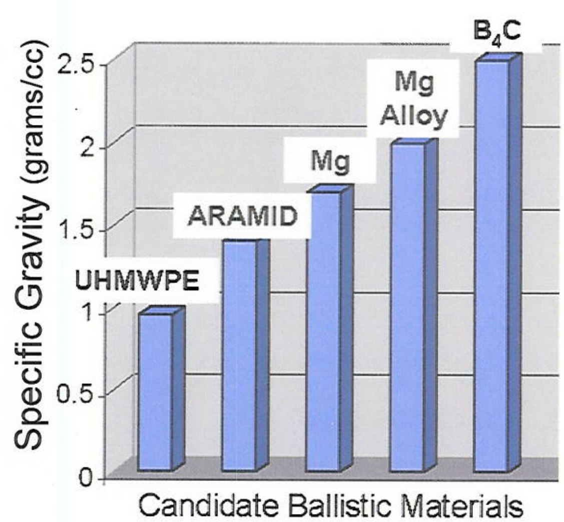

Figure 5. Candidate Commercial Ballistic Materials

The United States Army is interested in providing greater protection at lower weight. Magnesium based alloys are

of current interest because the density of magnesium (~1.74 g/cm^3) is approximately 35% lower than aluminum (~2.68 g/cm^3) and approximately 77% lower than steel. Moderate strength of commercially available wrought magnesium alloy plate, coupled with relatively low density, translates into a specific strength that is roughly equivalent with aluminum armor alloys as shown in Figure 6, where TUS and TYS represent the Tensile Ultimate Strength and Tensile Yield Strength respectively.

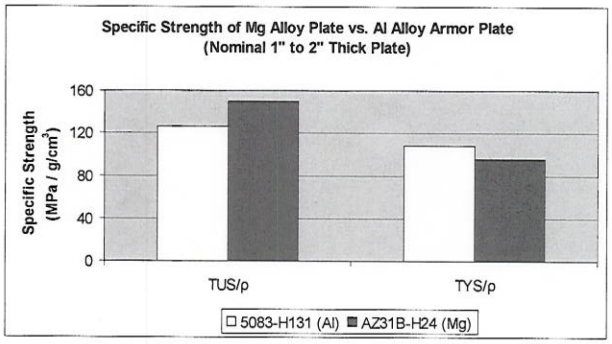

Figure 6. Specific Strength of Mg vs. Al Alloy Armor Plate

Although magnesium alloys have a relatively low elastic modulus, E, compared to other metal alloys, their low density provides their relatively comparable specific stiffness as shown in Figure 7.

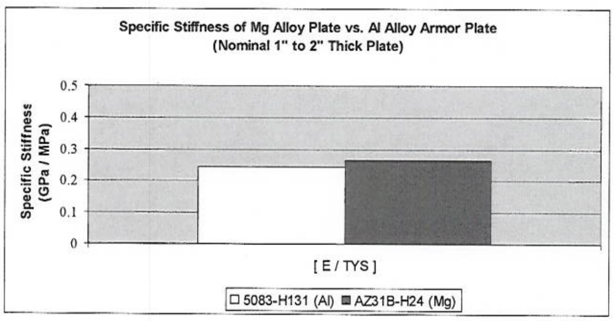

Figure 7. Specific Stiffness of Mg vs. Al Alloy Armor Plate

In general, there is a positive correlation between tensile strength and small arms ballistic performance in metal alloys, and higher stiffness typically contributes to enhanced energy absorption upon ballistic impact; therefore, one would predict a possible benefit in wrought magnesium alloy armor applications [Jones, 2008]. Although the tensile strengths of rolled magnesium alloys are traditionally lower than that of rolled aluminum armor alloys, magnesium may possess other unique characteristics, including superior vibration damping and differences in failure mechanisms that could provide for improved relative ballistic performance [Jones, 2007a].

Rolled plate of AZ31B-H24 and 5083-H131 were evaluated on an equivalent weight (i.e., areal density) basis. Figure 8 and Figure 9 show the ballistic performance of the small 0.22-cal fragment simulating projectiles (FSP) against thin gauge AZ31B-H24 plate. AZ31B-H24 outperformed 5083-H131 aluminum armor on an equivalent weight basis. The 5083-H131 data point is the minimum ballistic limit requirements per military material specification MIL-DTL-46027J (MR) [Jones, 2007b].

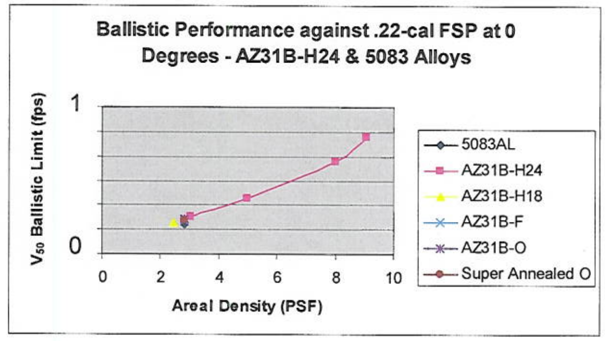

Figure 8. Estimated V_{50} ballistic limit of the .22-cal FSP.

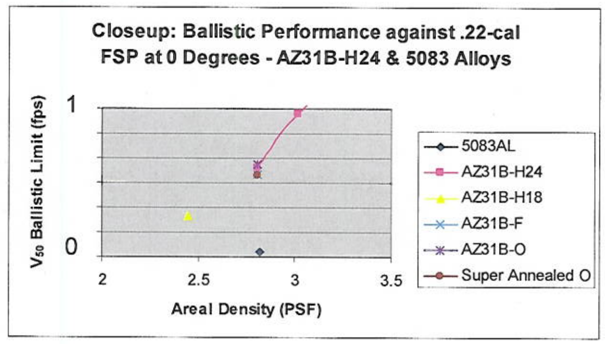

Figure 9. Estimated V_{50} ballistic limit of the .22-cal FSP.

Magnesium (Mg) [Emley, 1966] is the lightest structural and engineering metal at a density of 1.74 g/cm^3 that is approximately 1/5, 2/5, and 2/3 the weight of iron (Fe), titanium (Ti), and aluminum (Al), respectively. Figure 10 summarizes quasi-static specific mechanical properties and failure strain of three Mg alloys (AZ31B, WE43, and E675), and compares them with those of 4340 steel and Ti -6V-4Al alloy benchmarks. Specific properties mean properties are normalized by the material density and thus better incorporate both mass and space efficiency considerations. A density and an elastic modulus are two well known pseudo intrinsic material properties that are only strongly affected by a rule of mixture in elemental chemistries and phases. On the other hand, strength and strain to failure (e.g., ductility) are two well known extrinsic material properties that are very strongly influenced by alloying and manipulations in microstructure and/or deformation conditions. Most metals, including Mg alloys, exhibit very strong inverse proportionalities in strength and ductility. One classic exception of this trend is steel as shown in Figure 10.

AZ31B is a commercial grade Mg alloy available in a wide range of gages from 0.02" to 4" and contains magnesium, aluminum and manganese. The aluminum imparts strength to the system while manganese provides microstructural stability and improves corrosion resistance. WE43 [Mag Elek 2008a] and E675 [Mag Elek 2008b] are a semi-commercial grade intermediate strength and a developmental grade high strength Mg alloy, respectively. These Mg alloy systems are based on yttrium and rare earth alloying elements, which have been shown to exhibit higher quasi-static mechanical properties than AZ31B in expense of ductilities. Sheet and plate forms of these alloys are under development and aim to surpass the specific mechanical properties of AA5083. Mg alloys have abilities to be formed into complex shapes via the superplastic forming process [Sherby, 1989]. This fabrication method enables highly contoured and relatively deep components to be manufactured from sheet. The process involves heating the sheet to approximately 80% of its melting point, at which point it becomes highly plastic, and then blowing the part with high temperature compressed air on to a tool face or mold. This process has already been used to demonstrate the ability to form a generic helmet form (Figure 11).

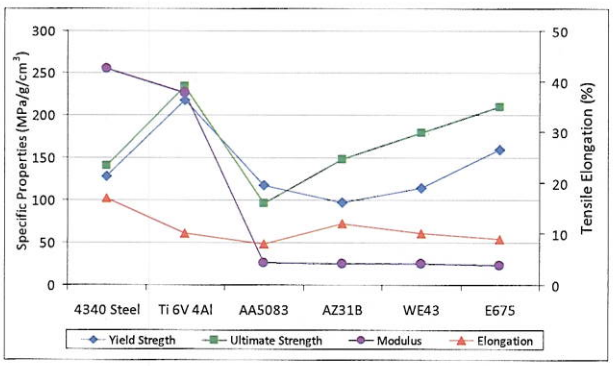

Figure 10. Specific properties and elongation comparison of Mg alloys, 4340 steel, and Ti-6V-4Al alloy.

In a metallurgical perspective, it is of utmost importance to improve and balance appropriate extrinsic materials properties, such as yield strength and ductility, under a wide range of strain rates by manipulating the microstructures to change the yield criteria and the deformation conditions in helmet hybridizations. Yield criteria are strongly influenced by alloy strengthening, Hall-Petch grain size strengthening, and multi-modal grain size distributions while deformation conditions are strongly affected by strain hardening and strain rate hardening. An ultimate metallurgical goal in helmet hybridizations is to simultaneously elevate both strength and ductility [Ma, 2006] of Mg alloys with appropriate strain rate sensitivities. Stiffness considerations are also equally important. Gain in stiffness (e.g., elastic modulus) is typically only possible through a metal matrix composites (MMC) concept. Currently, the only feasible way to simultaneously retain strength, ductility, and stiffness is through a multi-scale (hard phase reinforced nano- and coarse-grain matrix) composites [Ye, 2005] concept. Since Mg MMC and Mg multi-scale composites are in their infancy, any near term helmet hybridization concept should consider polymer based composites and commercial Magnesium alloys for stiffening and ballistic catcher performance.

With the limited ballistic testing to date, we have observed phenomena which appear to be important for maximum ballistic performance. Some of the compliant unidirectional materials have had problems with stopping pointed, relatively non-deforming projectiles. Our observations include negligible projectile deformation and tendency to not strip the metallic jacket. The use of a frontal layer of most metals tends to initiate the jacket stripping and point blunting. One theory as to why this is the case includes the relative magnitude of the shear strength of the frontal layer. A high shear strength target material will have a tendency to develop high shear stresses in the projectile, hence blunting and jacket stripping. A typical compliant laminate may have transverse shear strength of approximately 5 ksi or less. Most metals exhibit a shear strength of the order of 1/3 their tensile strength, or about 20-80 ksi (60-240 ksi ultimate strength) for armor steels, so the metals definitely have much higher shear strengths than the composites, and may be better candidates for strike face material given the greater extent of initial bullet deformation.

The challenge of developing a magnesium alloy/organic composite helmet will be multifold. Ballistic improvements must be measured not only in the constituents themselves, but their combinations as well. Developing scalable, cost effective processes to manufacture the magnesium alloy shell and the organic composite core will be critical. The influence of the forming process itself on the magnesium alloy will be especially critical; if the shell is formed from a flat sheet, it will be necessary to determine how the localized properties (thickness, microstructure, ballistic, and other) vary throughout the shell (Figure 11).

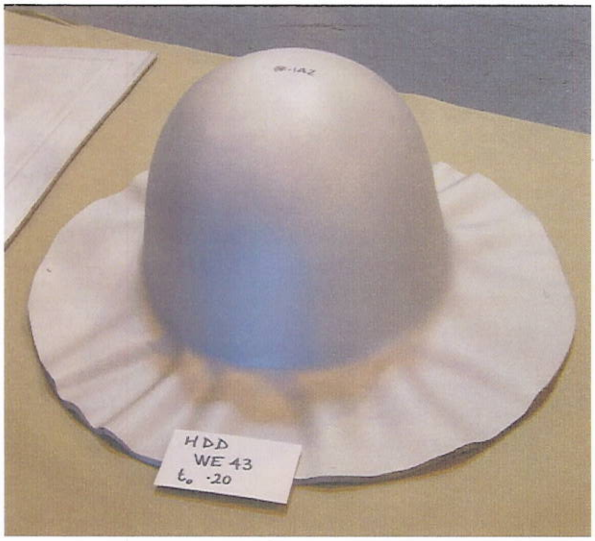

Figure11. Magnesium Shell

The motivation to hybridize can stem from one or more needs. For example, hybridization may enable improved ballistic resistance or structural durability. It can also be done for materials availability reasons, as well as flame retardance (e.g., use of aramid/UHMWPE hybrids). Finally, hybridization may provide a more competitive cost approach; a relatively inexpensive fiber composite can be used in conjunction with a very expensive composite. Effective hybridization must address several considerations. Long term durability, co-processing and ease of manufacture, repair, etc. Testing the constituent materials in isolation will likely not provide all the information to improve the bulk response of a hybridized material system.

3b. Design Approach

Helmet design – and more specifically, the design of its shape and components – is critical to the overall effectiveness of the helmet. Many factors influence helmet design, not the least of which is area of coverage, conformance to different populations of head shapes and sizes, and extraneous features such as interfacing with body armor and weapons systems. The goal of the present research is to consider new, and thoroughly alternative approaches to the design not just of the shell itself, but the means by which it is structurally integrated into the helmet ensemble.

3.b.1 Integrated helmet stiffening

As discussed earlier, some of the most promising ballistic materials (e.g., thermoplastic based fibers and resins) suffer from a structural limitation: they are too compliant. To remedy this, and provide the desired combinations of both static and dynamic structural integrity, previous research efforts successfully demonstrated hybridization with stiffer materials (e.g., carbon/epoxy or carbon/Nylon) as a potential solution. However through structural analysis, it was demonstrated that it may not be necessary to apply the carbon skin entirely over the helmet; this provides an opportunity to consider a novel "chassis" approach that relies as much on *design* as it does on materials. A graphic of the rim stiffening chassis is shown in Figure 12. The notion of relying on design to influence end item structural properties is not new; for example, the use of "pi" joints and hat stiffeners is common in the composite air frame industry to maximize the mass-efficiency of the overall component. Helmets, and ballistic helmets in particular, have not been dominated by stiffness requirements but rather other properties (e.g., crash, impact, ballistic resistance).

Figure 12. The Integrated Helmet Chassis

There are several advantages to this concept:

- Selective stiffening for maximum weight reduction
- Reduced part count for ease of manufacture
- Elimination of bolt holes and drilling into ballistic shell
- Rapid assembly and installation of helmet pads, suspension, and straps
- Accommodating sizing range by selecting several chassis with less numerous ballistic shells

Previous research efforts demonstrated the ballistic and structural advantages of the rim stiffening chassis. However, recent analysis suggests that the chassis concept has the potential to enhance the resistance to a blast event. A computer model was executed in which the baseline ACH shell was subject to an overhead blast event of known intensity. This was then compared to an ACH shell with an integrated stiffening chassis. A comparison of the resulting deformations of both types of helmets is shown in Figure 13. Though preliminary, the analysis suggests it is possible to engineer a different – and possibly more desirable – response to a blast event. The results are presented here simply as an example of the influence of both materials and design not only on ballistic response but blast events as well.

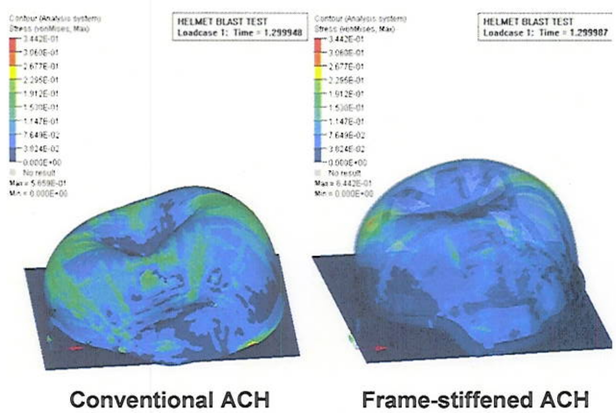

Figure 13. Comparison of Helmet Deformations at Different Time Intervals

3.b.2 Implications of Design on Blast

It is anticipated that more innovations will occur in the development of head-borne concepts to address the adverse influence of blast. Considerable research is underway, primarily in the medical communities, to correctly identify the principal mechanism or *mechanisms* responsible for traumatic brain injury (TBI). In the interim, is possible to devise a purely engineering approach to the problem of how blast energy arrives, impinges, and ultimately interacts with the helmet shell, suspension, padding and human head. Modeling accuracy would increase as better estimates of skull and brain properties become available.

Helmet shape influences the means by which the overall helmet responds to a blast event. Historically, helmets have been somewhat hemispherical. For blast and other reasons, alternative geometries are being explored that include the use of flat and prism surfaces. It is not anticipated that this approach will provide a significant increase in the blast resistance of a helmet, but combined with innovations in the suspension, padding, and ballistic shell material, they may contribute to overall mitigation of an adverse blast event. Figure 14 shows the baseline ACH and add-on shell. Purely for comparative purposes Figure 14 shows a simulation of helmet deformation behavior for the conventional ACH and the alternative "flat surfaced" hex helmet shell.

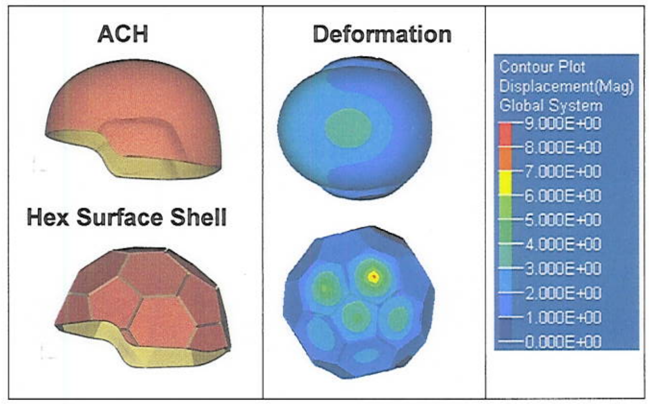

Figure 14. ACH geometry vs. Hex shell geometry

4. SUMMARY

The purpose of this work was to provide evidence that there are alternative materials and design approaches under consideration in the development of the next level of performance for head-borne protection systems. The motivation of presenting this information is to stimulate less conventional approaches to helmet material and design selection so that a broader and perhaps more severe array of threats and operating condition requirements can be met without an excessive weight penalty. U.S. helmets have always represented state-of-the-art in the use of materials, manufacturing process, and geometric configurations that best meet prevailing threats and needs of the military. The emergence of new materials, and especially combination of materials through hybridization and co-processing, provides an opportunity to develop a broader "solution space" for ballistic performance in future systems. Similarly, while the exact mechanisms causing blast-related injuries to the head are still actively being researched and validated, the use of computer modeling and preliminary prototype fabrication has enabled alternative approaches to considering the implications of blast requirements on helmet materials and design selection.

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